Designation: E3045 − 16

Standard Practice for Crack Detection Using Vibroacoustic Thermography[1]

This standard is issued under the fixed designation E3045; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 *Purpose*—This practice covers procedures required to conduct an examination of components using vibroacoustic thermography.

1.2 *Application*—The vibroacoustic thermography process has been used for component inspections in the aircraft, power generation, automotive, and other industries for testing new and serviced components, both coated and uncoated. Current applications are mostly targeting metallic components, but composite and ceramic component applications are under development.

1.3 *Background*—Vibroacoustic thermography is a new technique within the area of active thermography. The technique was first published by Henneke, et al. in 1979 (**1**)[2] and has been expanded on and popularized by Favro, et al. (**2**). During the test a defect thermal response resulting from a short burst of ultrasonic energy typically in the range of 15 kHz to 40 kHz is detected by an infrared camera. The ultrasound coupled into the component being tested can activate a thermal response in defects with contact areas that can move against each other, that is, cracks and delamination. There are different energizing and coupling techniques that are commonly used depending on the needs and capabilities. These variations and the down selection process are not included in the procedure and should be developed/optimized by experimentation for each new component application.

NOTE 1—Vibroacoustic thermography is typically sensitive to tight planar defects (**3**). Volumetric defects such as porosity, inclusions, open ruptures or cracks in wide-open areas, will not typically result in an indication. Therefore, an augmenting method should be conducted to detect volumetric defects.

NOTE 2—Vibroacoustic thermography is a surface examination but has demonstrated detection sensitivity for subsurface defects including back wall defects for thin components (**4**), (**5**). Care should be taken when developing vibroacoustic thermography for the detection of subsurface defects.

1.4 **Warning—**Vibroacoustic thermography requires the energization of the test article with vibrational energy. During energization, the complete component may be excited with vibroacoustic (vibration) energy for as long as several seconds. The development of this test for a new application requires special measurements, precautions and attention to component response. The component design engineer and the NDE engineering specialist, knowledgeable of this technique should be satisfied that the test will not cause damage or reduction of service life.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E168 Practices for General Techniques of Infrared Quantitative Analysis (Withdrawn 2015)[3]

E1213 Practice for Minimum Resolvable Temperature Difference for Thermal Imaging Systems

E1252 Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis

E1311 Practice for Minimum Detectable Temperature Difference for Thermal Imaging Systems

E1316 Terminology for Nondestructive Examinations

E1933 Practice for Measuring and Compensating for Emissivity Using Infrared Imaging Radiometers

E2585 Practice for Thermal Diffusivity by the Flash Method

2.2 *ASNT Standards:*[4]

SNT-TC-1A Recommended Practice, Personnel Qualification and Certification in Nondestructive Testing

ANSI/ASNT CP-189-2001 Standard for Qualification and Certification of Nondestructive Testing Personnel

2.3 *ATA Standards:*[5]

ATA-105 Guidelines for Training and Qualifying Personnel in Nondestructive Testing

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[1] This test method is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.10 on Specialized NDT Methods.

Current edition approved April 1, 2016. Published April 2016. DOI: 10.1520/E3045-15

[2] The boldface numbers in parentheses refer to a list of references at the end of this standard.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.

[5] Available from Air Transport Association, 1301 Pennsylvania Avenue, Suite 1100, Washington, DC 20004–1707.

2.4 *U.S. Publications:*

MIL-HDBK-1823A Department of Defense Handbook: Nondestructive Evaluation System Reliability Assessment

3. Terminology

3.1 *Abbreviations:*

3.1.1 *IR*—Infrared

3.1.2 *MWIR*—Mid-Wave Infrared

3.1.3 *LWIR*—Long-Wave Infrared

3.1.4 *NDE*—Non-destructive Examination

3.1.5 *ROI*—Region of Interest

3.1.6 *NETD*—Noise Equivalent Temperature Difference

3.1.7 *CCD*—Charge Couple Device

3.1.8 *MSDS*—Material Safety Data Sheets

3.1.9 *SPDS*—Safe Practice Data Sheets

3.1.10 *TBC*—Thermal Barrier Coating

3.1.11 *ASNT*—American Society for Nondestructive Testing

3.1.12 *ANSI*—American National Standards Institute

3.1.13 *ATA*—Air Transport Association

3.1.14 *FOV*—Field of View

3.1.15 *POD*—Probability of Detection

4. Summary of Practice

4.1 *Personnel Qualification/Certification*—Vibroacoustic thermography is a new active thermography technique within the method of infrared and thermal testing. As the technique develops, it is expected that several sub-techniques for energizing will be developed, refined, and documented. The current energizing variations require competence in areas of materials, mechanics, and heat transfer. Therefore, early users are expected to be well versed in these areas to ensure conservative applications. Because there is no existing single NDE method that matches all of the necessary skills, this first procedure requires the responsible control of a certified Level III in the method of infrared and thermal testing in accordance with ANSI/ASNT CP-189 or ASNT, SNTTC-1A. It is recommended that the Level III, under consultation with the responsible component engineer, develop the necessary supplemental training requirements for Level I and Level II personnel. Inspections shall be conducted by NDE Level I or Level II inspection personnel certified in accordance with ANSI/ASNT CP-189 or ASNT, SNTTC-1A. The NDE Level I should be qualified to properly perform specific calibrations, specific NDE, specific evaluations and record results according to written instructions. The NDE Level II should be qualified to set up and calibrate equipment, to interpret and evaluate results with respect to applicable codes, standards and specifications and to organize and report the results of NDE.

4.2 *Vibroacoustic Thermography Test System*—The system consists of an ultrasonic exciter, an infrared camera, and operating software to sequence the test and capture the result. The exciter is an ultrasonic piezoelectric transducer stack that may commonly be used for ultrasonic welding (plastics industry) or vibrations testing. Depending on the specific method of energization, a booster (amplifier) or a horn may also be used to augment, phase, couple or focus the ultrasonic energy. Energization occurs for the first 0 - 8 seconds of test again depending on the energization method. During this time, the IR camera is triggered to capture resulting active heating of the component defects. The images are labeled and stored for slow motion play back of the simple vibroacoustic thermography movie, or for further analysis.

4.2.1 *Ultrasonic System*—Includes power supply and component fixture. Examples of these systems include a piezoeletric shaker, or ultrasonic welder system. Specific power ratings (watts) and frequency (kHz) for the power supply and the converter are essential to the vibroacoustic thermography inspection process and shall not be changed or modified without contacting system manufacturer. Typical power ratings for a piezoeletric shaker system range from 800W - 4000W with typical frequencies ranging from 14,000 Hz - 100,000 Hz. For ultrasonic welder systems, booster gain ratio, horn shape and horn material also are essential to the vibroacoustic thermography inspection process and shall not be changed or modified without contacting system manufacturer.

4.2.2 *Infrared Thermal Camera*—Thermal camera must have the sensitivity to achieve the required defect Probability of Detection (POD) (**6**), (**7**), (**8**). Cooled MWIR (InSb) thermal cameras usually provide the best sensitivity (around 20 mK or better), whereas LWIR microbolometer are generally less sensitive but may be adequate in many applications. Frame rates ≥30 Hz are generally sufficient for vibroacoustic thermography measurements. Any resolution is adequate so long as the camera is close enough to the specimen to resolve defect indications as in Practice E2585, subsection 6.1. This can be determined prior to test by use of a setup specimen having a defect in it of similar thermal signal to that of the defects of interest in the inspected parts.

4.2.3 *Minimum Software Requirements*—The software should provide a method for triggering the excitation of the part and recording the part response. The software should also provide a method for reviewing and analyzing the results.

4.3 *System Calibration:*

4.3.1 If detection of certain critical defects is an engineering requirement, then a rigorous evaluation of capability and reliability is required, including a proper POD study. Such an evaluation would consider process variability due to excitation, vibration, crack location and orientation, crack closure, crack thermal response variability, non-uniformity of thermal camera field, and infrared detection. General principles and guidelines for POD evaluation can be found in MIL-HDBK-1823A.

4.3.2 If there is no engineering requirement on defect detection, system capability can be estimated from samples with relevant defects or samples with similar simulated defects, called reference standards or reference components. Use of these samples can help confirm that the relevant defects are within the usual resolution and sensitivity limits of the IR NDE system.

4.3.3 Once reference standards or reference components have been established, the same sample(s) can be retested later to help confirm proper system operation. Although it is not possible to define a universal reference standard, the following guidelines for development of reference and calibration standards will apply to most commonly encountered NDE situations:

4.3.3.1 The reference sample should be constructed of similar material as the actual part.

4.3.3.2 The reference sample should have similar surface preparation as the actual part.

4.3.3.3 The reference sample should contain real or simulated defects which correspond to worst and best case defect scenarios, with a reasonable range of severity, depth, and/or size between these limits.

4.4 *Development of Evaluation Criteria*—A basis for accept/reject decisions must be developed. Procedures should be developed by various engineering department representatives in harmony with certified Level III personnel, who are familiar with the thermographic inspection equipment to be used, as well as the part to be inspected, its function, composition, and defect and failure modes.

5. Specific Practices

5.1 *Cleaning and Surface Preparation:*

5.1.1 The cleaning and surfaces preparation process should be determined in conjunction with the creation of the inspection process specification for the specific part and should be used to remove or limit the false indications that may arise from foreign objects or contamination. The following is a description of the minimum recommended cleaning and surface preparation requirements.

5.1.2 Visually inspect the examination area for defects that vibroacoustic thermography is not specifically designed to detect. This may include dents, gouges, and other open indications where vibro-acoustically excited features will not interact to generate heat. Remove foreign objects, or contamination that could interfere with the inspection. This includes any loose debris that may move on the surface. Excess grease or oil should be wiped away.

5.1.3 In rare cases the emissivity of the surface may be low enough to reduce thermal emission from relevant indications. In this case the surface emissivity may be increased by application of a suitable coating. An example process for applying a coating to improve surface emissivity of a part is described in Appendix X1.

5.2 *Reference Standards:*

5.2.1 There are two types of reference standards currently used for vibroacoustic thermography: cracked standards and thermoelastic standards. Cracked standards require real cracks to cause a repeatable indication for standardization or reference. Thermoelastic standards are typically attached polymers that heat up characteristically upon energization. Any of the following standards may be used for the purpose of assuring a proper energization/ imaging process as well as establishing a level of confidence for defect detection.

5.3 *Reference Component*—A component(s) having a known natural or fabricated defect in it may be used for a reference standard. The reference standard should contain at least one defect of current and specific concern. A permanent record of a detailed defect map of the reference component shall be maintained. This record shall include defect location, length and orientation. The original indication response shall be stored for reference. Additionally, an indication response for the reference component shall be included in the inspection report for each heat or batch of components and for every shift or work per inspection station.

5.4 *Quality Indicator*—A quality indicator is a simple and cost effective polymer tape consisting of an adhesive poster strip attached to the test article (that is, 3M Command Poster Strips). The reference standard should always be used with an attached quality indicator in the ROI. Quality indicators heat up upon energization of the test article to verify system operation. It is recommended that quality indicators be used on every component of the testing cycle.

5.5 *Examination Coverage*—As with all image based NDE, the detection capability is limited by the spatial resolution of the acquired image. In cases where the instantaneous field of view is insufficient to resolve the indication (that is, measured millimetres per pixel times 2-5 pixel safety factor is less than the indication size), a special qualification should be conducted to demonstrate adequate detection of relevant indications. The nature of the examination allows for repeat magnified examinations to zoom in on an indication for characterization and orientation details. The following are requirements for image and coverage of the examination.

5.5.1 *Image Area Covered for Each Energization Cycle*—It is recommended that the field of view (FOV) be sized to assure that the reportable or rejectable defect dimension is no smaller than 2-5 pixels of Camera CCD element coverage for each image. For large components where the ROI could be larger than the camera field of view, multiple examinations shall be needed.

NOTE 3—For detection, the defect need not be spatially resolved, since the thermal diffusion broadens the detectable indication. If needed for characterization, additional views with a closer camera or telephoto lenses may be used.

5.5.2 *Camera Focus*—It is recommended that the entire camera FOV be in focus during the vibroacoustic thermography test. The camera is considered to be in focus if the required spatial resolution to detect the smallest indication of interest is maintained across the camera FOV. In cases where this cannot be achieved (that is, because of part geometry or camera optics) the camera FOV shall be considered reduced to the region of the CCD that is considered in focus.

5.5.3 *Angle of Incidence*—The entire ROI shall be imaged from an angle of incidence of less than 45 degrees from normal to the target surface, unless this line of sight is not allowed due to mechanical restrictions such as component features, assembly interference, practicality and accessibility. If larger angle of incidence is used, a specific qualification shall be required.

5.6 *Vibroacoustic Thermography Setup and Camera Calibration:*

5.6.1 Setup the vibroacoustic excitation system to excite the part in accordance with the manufacturer's specifications and best practices determined by the responsible engineer and Level III described in the inspection process specification for the part under test using the vibroacoustic thermography technique.

5.6.2 Ensure that the IR camera is fitted with a lens that fulfils the FOV and spatial resolution requirements appropriate to the application. Consult inspection system manufacturer or IR Camera manufacturer for lens recommendation. The recommended camera lens may be close to 50 mm.

5.6.3 The camera should be corrected for bad pixels and non-uniformity, and this correction should be repeated or validated on a regular basis. Consult inspection system manufacturer or IR Camera manufacturer details on non-uniformity and bad pixel correction recommendations.

5.6.4 It is suggested that the components to be tested should be at ambient temperature. Use an enclosure as necessary to eliminate IR reflections that may interfere with indication detection or interpretation. Components with low emissivity (that is, highly reflective) surfaces are very susceptible to background interference and emit less infrared radiation. The low emissivity surface of the component will reflect any background heat and can cause the system operator to misinterpret the inspection result. Low emissivity surfaces will emit less radiation making indications look smaller than they would on non reflective surfaces. Reflective surfaces can also make system sensitivity lower. In cases where the system sensitivity is suffering due to low surface emissivity the surface emissivity may be increased by application of a suitable coating. An example process for applying a coating to improve part emissivity is described in Appendix X1.

5.6.5 Position the IR camera so that it can view the ROI of the part. Focus the image.

5.7 *Vibroacoustic Thermography Test Procedures:*

5.7.1 *Excitation System Setup*—The ultrasonic source shall be held to the component by a suitable mechanical device with a controlled loading force. This is best done using a fixture designed specifically for this purpose. Couplant materials are recommended to minimize contact surface damage, particularly in soft materials but reduce the amount of excitation energy entering the part. Typical couplant materials are paper, cardstock, duct tape, and Teflon. For some exotic alloys such as titanium alloys, contact with specific materials is not allowed. This must be fully researched before selecting a coupling material. Also some standard procedures disallow metal on metal contact for test instrumentation.

5.7.2 Verify system is setup correctly. Prior to the first inspection of the day, verify that the excitation system is set to the appropriate parameters for the part to be inspected as defined by the part inspection process specification for vibroacoustic thermography. It is suggested that a sample test specimen with known defect should be used to ensure the system is in proper working order. (**Warning—**In some cases, the specimen energization may result in a loud noise; it is recommended to wear hearing protection.) (**Warning—**It is always recommended to wear proper personal protective equipment for the test environment including safety glasses and hearing protection.)

5.7.3 Initiate the test. The test should record all of the infrared camera images for at least two times the excitation time. Longer times may be necessary to see the full dissipation of heat (time required to see dissipation is primarily a function of thermal diffusivity).

5.7.4 During the test, visually observe the live image being captured by the infrared camera watching for indications and excess motion of the part relative to the camera. Some post processing algorithms will give artificial indications (that is, outlining of the part) if too much motion between the camera and part is present.

5.8 *Indication Detection*—Indication detection and subsequent interpretation steps shall be performed for all vibroacoustic thermography system image files created.

(1) Review the relevant inspection process documentation for detailed instructions as needed.

(2) View the entire video sequence in the ROI. Indications will typically appear as bright areas (depending on software settings) that were not present before energization.

(3) If an indication appears, pause the video sequence at the time the indication first appeared and note the indication appearance. The early indication image typically shows the shape characteristics of the indication. Then allow the video to progress while observing the continued formation of indication features and heat conduction away from the heat source of the indication. Surface heat sources will peak in thermal emission at the time the excitation of the part stops. Subsurface heat sources will emerge later. Heat from all sources will be conducted away and cause a broadened warmer region that loses the shape characteristics of the heat source. It is also important to observe the indication's shape and orientation at the edge of the component. Note that the entire defect may not exhibit thermal emission. After an indication is observed, visual assessment of the indication on the part is recommended to determine the complete characteristics of the indication (such as connection to an edge or connection between indications).

(4) Software image enhancement tools may be used to improve sensitivity and image detail. These include post-processing filters like averaging, de-noising, sharpening or more sophisticated algorithms like pulse-phase analysis with subsequent color combination that produce a single color image. Consult software manual or manufacturer's instructions to ensure that post processing algorithms are being used and interpreted properly.

5.8.1 *Non-Relevant Indications:*

5.8.1.1 Non-relevant or false indications are defined as vibroacoustic thermography system signals whose source or sources are from conditions not associated with defects, degradations or discontinuities of interest to the inspection process.

5.8.1.2 "Noise" or other NDE process-induced sources, geometric or design-related sources can cause non-relevant indications. Known examples include IR reflections, heating at the ultrasonic horn contact location, heating at any other mechanical contact points between vibrating components, solid objects or material in cooling passages, dirt or oil on the specimen.

5.8.1.3 The qualified vibroacoustic thermography system operator determines nonrelevant indications using the related inspection process specification as a guide.

5.8.1.4 The location of any non-relevant indication shall be mapped if the operator judges it could mask possible reportable indications.

5.8.1.5 All other indications whose source or sources are typical of conditions associated with defects, degradations or discontinuities, are relevant indications and shall be further evaluated in 5.8.2.

5.8.2 *Relevant Indications:*

5.8.2.1 Evaluate the results of the test by observing localized thermal response (hot spots) which begin heating at the beginning of the ultrasonic pulse and reach a peak at the end of the pulse.

5.8.2.2 Identify all linear or crack-like indications in the base metal or metallic coating layer. Note any special features of the indication needed to describe the properties of the indication, such as shape or localized heating which may be limited to only part of a crack or crack-like indication. Examples include cracks where only the crack tip area shows a thermal response, or intermittent heating along the length of a crack.

5.8.2.3 Confirmation of TBC disbonds can be done using pulsed thermography inspection of the component. If TBC disbonds cannot be confirmed by direct visual inspection, the indication shall be considered as originating in the bond coat layer or base metal.

5.8.2.4 Measurement of the length of base metal or metallic coating indications shall be made when specified by the inspection process specification.

5.8.2.5 Reference the applicable component, drawing or other document to determine any additional areas for inspection. Note, if needed, the image can be magnified using the software zoom feature to aid interpretation.

5.9 *Reporting:*

5.9.1 *General*—General archiving and documentation requirements must follow accepted NDE reporting procedures (for example, reports should include inspector name, equipment used, part inspected, date, time, etc., in addition to a detailed description of the defect encountered). However, the fact that IR NDE methods make use of image data rather than a single numerical result requires that additional steps be defined. A wide range of formats for IR NDE results exists, ranging from full image data to plot and numerical analysis of the image. The particular quality procedure or specification that is approved by the appropriate Level III personnel will clearly identify the reporting requirements for the specific application. Data types and recommended formats for archiving and documentation are listed below:

5.9.1.1 *Image Data:*

(1) Single image formats:

(a) 8-bit images

(b) 16 bit images

(2) Multiple image formats:

(a) Extended consecutive image sequences

(b) Non-consecutive gated image sequences

5.9.1.2 *Plot Data:*

(1) 3-D perspective plot

(2) Horizontal and vertical line profiles

(3) Histogram

5.9.1.3 *Numerical Data (to be defined by CEO):*

(1) Mean amplitude

(2) Max and min amplitude

(3) Standard deviation

(4) Signal to noise

(5) Length

5.9.2 *Reportable Indications*—These indications could be any number of conditions and therefore, the number, size and position of the indications are covered in the inspection process specification.

5.9.3 *Marking*—Parts should be identified (Accept/ Reject) as appropriate per company requirements.

5.9.4 *Reporting Procedures*—Some application specific inspection requirements call for a written report including information such as discontinuity locations, dimensions, etc. or a sketch showing the indication position. Other cases call for marking discontinuity locations on the part. Where no special reports are required, it is recommended that the following applicable information be recorded and archived as a minimum for each item:

5.9.4.1 Date of examination,

5.9.4.2 Inspector name,

5.9.4.3 Inspector certification level,

5.9.4.4 Part description,

5.9.4.5 Process specification number and revision number,

5.9.4.6 Acceptable, unacceptable or reportable indications,

5.9.4.7 Details of unacceptable or reportable conditions,

5.9.4.8 All appropriate system settings that would allow the operator to exactly repeat the test.

6. Acknowledgement

6.1 A vendor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders.

7. Safety

7.1 Applicable Material Safety Data Sheets (MSDS) and Safe Practice Data Sheets (SPDS) must be available and reviewed for all solvents and materials used in any inspection process specification.

7.2 All precautions related to the use, handling, storage, and disposal of the solvents and materials used in any inspection process specification, as specified in the appropriate MSDS and SPDS, must be observed.

7.3 All plant safety precautions shall be used when following any inspection process specification. Safety glasses and hard hats shall be used where applicable. Waste disposal must be conducted in accordance with all federal, provincial, state, and local government environmental regulations.

7.4 Do not touch any part of the ultrasonic gun during energizing. Severe friction burns could result!

7.5 It is recommended that operators use adequate hearing and eye protection during use of vibroacoustic thermography systems.

APPENDIX

X1. IMPROVING PART SURFACE EMISSIVITY USING A COATING

(Nonmandatory Information)

In rare cases the emissivity of the surface may be low enough to reduce thermal emission from relevant indications. In this case the surface emissivity may be increased by application of a suitable coating. An effective method for improving surface emissivity is by painting the surface with graphite or flat black paint. The following procedure has been provided as a broad guideline for improving surface emissivity of a sample.

X1.1 General

X1.1.1 Ensure the part is free of dust, dirt, oil, water, couplant, etc. Use solvent if necessary (alcohol, acetone, mild soapy water, etc.).

X1.1.2 If the part is washed, allow it to dry fully.

X1.1.3 Determine if part can be coated or painted.

X1.2 Highly Reflective Parts That Can Be Coated or Painted

X1.2.1 Recommended Coatings:

X1.2.1.1 Water-based black tempera paint—can be easily washed off.

X1.2.1.2 Peelable flat black paint—can be peeled off after testing is complete.

X1.2.1.3 Non-aqueous penetrant developer.

X1.2.2 Spray or roll paint on surface. Apply paint in thin layers. Do not apply in one thick layer.

X1.2.3 Water based paints may not adhere well to some metal or pre-painted surfaces. In these cases a primer layer, which may be non-uniform, mottled or contain bubbles maybe applied. Successive uniform layers should be applied before this layer has completely dried.

X1.2.4 Coating should appear uniform with no runs or flaking.

X1.2.5 No metal surfaces of inspection interest shall be visible after coating application.

X1.2.6 Allow coating to dry.

X1.2.7 Remove surface preparation after testing is complete.

NOTE X1.1—Adjusting the emissivity setting on most infrared cameras affects the displayed image and temperature measurements, but does not affect the digital data which is typically used for IR NDE applications.

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